

Improvement of the Sintered Surface and Bulk of the Product Via Differentiating Laser Sintering (Melting) Modes

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Abstract. Selective laser sintering (melting) enables using metal powdered materials to manufacture products of any geometrical complexity, requiring no preliminary costs to prepare processing equipment. However, quality of the sintered surface is often inadequate as against the product manufactured traditionally. Manufacturing a high quality product requires solution of such vital task as prediction of the sintered surface roughness. The authors address to the effect of laser sintering modes on roughness of the surface, sintered of copper powdered material PMS-1 (IIMC-1). The dependence of roughness of the surface layer sintered of copper powder material PMS-1 upon sintering process conditions is expressed mathematically. The authors suggest differentiating sintering modes to improve the sintered surface and the bulk of the product and dividing them into rough, semi-finishing, and finishing ones.

Introduction

Rapid prototyping is widely applied in the present day economy to reduce costs of manufacturing competitive products. Products of any geometrical complexity can be constructed on the base of these technologies requiring no preliminary costs for preparation of processing equipment. A lot of rapid prototyping technologies, differing from each other by the applied material and methods of forming the product, are available these days [1-3]. They include stereolithography (SL), fused deposition modeling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), used in foundry engineering, industrial designing, manufacturing products for medicine (implants) etc. Selective laser sintering (melting) is the most promising method to produce a physical copy of various objects using powdered materials on the base of a 3D CAD-model. So, this method enables manufacturing of functional products. This technology makes use of diverse raw materials, ranging from plastic to various metal alloys [4-6].

Alloys, which can be hardly produced relying on conventional technologies, are the products of mixing various powdered materials. The fields of SLS (SLM) application depend on physical and mechanical properties of the material and quality of the sintered surface. Synthesizing complex products of metal powdered materials with certain geometrical, physical and mathematical properties makes it possible to expand application fields of this technology [7]. Thermal effect of laser output on the powdered material is important for quality of the product and can cause rather complex physical phenomena of diverse nature, whereas high quality products can be manufactured in the certain



conditions only [8, 9]. Post-processing is used in most cases to improve quality of the sintered products. However, the methods of post-processing do not support the control over geometrical and micro-geometrical characteristics of the synthesized surfaces, necessitating, therefore, application of technological methods to produce a high quality surface layer [10, 11]. Assessment of appropriate modes providing certain quality of the surface layer of the sintered metal powdered materials is a burning and difficult issue. In this paper the authors address to the effect of laser sintering conditions on roughness of the sintered surface of copper powdered material PMS-1. The dependence of roughness of the surface layer sintered of copper powder material PMS-1 upon sintering modes is expressed mathematically. The authors suggest differentiating modes of sintering to improve the sintered surface and bulk of the product and dividing them into rough, semi-finishing, and finishing ones [12-15].

Stabilized copper powder PMS-1 is widely applied in various branches of industry. Particles of the powder have a spherical form with the nominal dimension of 0.007 mm, bulk density is 1.25-1.9 g/cm³. Thermal conductivity factor of copper powder is 3.6×10⁻³W/(m·°C), and melting temperature is 1030-1070 °C [16, 17].

Roughness of the sintered layer is assessed by the microscope LEXT OLS 4100 (OLYMPUS).

The experiments are carried out by the self-developed selective laser sintering facilities, which support adjustment of all processes of sintering. This machine is a technological laser jet to form surfaces of the products with complex spatial configuration, consisting of ytterbium fiber laser LK – 100 – V, three-dimensional desk, PC, system of the numerical control program and self-written software. Step motors are used to move the ball screw assembly along the coordinates X, Y, Z. The ytterbium fiber laser with the wavelength 1.07 μm makes it possible to adjust the power in the range 10-100 W. The constant output power and accuracy of fiber laser focusing ensure quality and precision of manufactured products. The laser beam is controlled by special software in the operation area of the size 100x100x100 mm, so scanning of any needed contour can be performed. As soon as a single layer is sintered the desk is lowered by the step motor as required (thickness of the layer) [18].

Results and Discussions

When manufacturing products by selective laser sintering, the quality of the surface differs from that of the bulk of the product. Synthesizing the bulk requires assignment of the sintering conditions, providing high roughness of the sintered surface; that is necessary to ensure stable cohesion between the layers and avoid delaminating. The outer surface of the product is to be synthesized in other conditions, providing low roughness. Roughness of the sintered surface depends on a number of factors, related to sintering conditions, properties of the powdered material, technical solutions. In the course of the experiments principal adjustable parameters are revealed, which influence on the formation of the sintered surface micro-section. They include laser output power (P), velocity of laser beam displacement (V), scanning step (s), preliminary pre-heating temperature of powdered material (t), impact of the shielding gas – argon and mechanical activation of the powder [19]. First, preliminary pilot experiments are conducted to determine the appropriate conditions of sintering, when a single layer does not go into pieces at a touch, i. d. it has some mechanical strength without considerable deformation. Insufficiency of laser power below 15 W and velocity of laser beam displacement faster than 3000 mm/min for sintering the powdered material has been revealed in the experiments aimed at detecting the appropriate conditions of sintering copper powdered material PMS-1. The power exceeding 30 W and velocity less than 200 mm/min cause intense oxidation and powder inflammation.

The increase in the scanning step more than 0.3 mm keeps single tracks from sintering, so a single layer fails to form. Increasing temperature of the powdered material pre-heating has a positive effect on the strength of a single layer. The samples of the powdered material PMS-1 are made in the following conditions: laser output power (P) is varied in the range 15 to 30 W, laser beam is moved with the velocity (V) 200 to 3000 mm/min, scanning step (S) is 0.1 to 0.3 mm, and temperature of the powdered material pre-heating (t) is 26 to 200 °C. Samples of 20 mm long and 10 mm wide sintered layer are produced for the purposes of experiments.

A four-factor experiment is conducted to identify a mathematical dependence of the sintered layer roughness upon the process conditions of sintering. Level of factors and variability intervals are assigned according to the results of preliminary pilot experiments. The resulting regression equation is in the form of an expression as follows:

$$R_z = 356 + 15 \cdot P - 0.1 \cdot V - 0.057 \cdot t + 425 \cdot S \quad (1)$$

The dependencies of surface roughness on the laser sintering modes plotted using expression (1) are shown in figure 1.

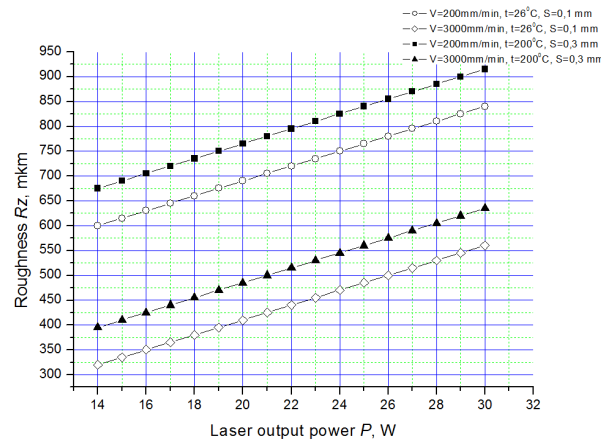


Figure 1. The roughness R_z vs. sintering conditions

Changing the beam power in the range 15 to 30 W resulted in increasing the surface layer roughness R_z from 600 to 830 μm , figure 2 and figure 3, and cracking appeared due to the higher thermal expansion stress. Thus, the beam power has a great effect on the surface roughness of laser deposited coatings. Changing the beam displacement velocity from 3000 to 200 mm/min results in increasing the roughness from R_z 320 to 600 μm , figure 4 and figure 5.

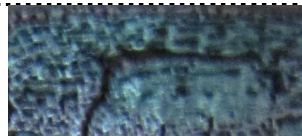


Figure 2. Micrographs, showing surfaces of the sintered copper samples (x2), process conditions of sintering: $V=200$ mm/min, $t=26$ °C, $S=0.3$ mm, $P=30$ W.



Figure 3. Micrographs, showing surfaces of the sintered copper samples (x2), process conditions of sintering: $V=200$ mm/min, $t=26$ °C, $S=0.3$ mm, $P=15$ W.



Figure 4. Micrographs, showing surfaces of the sintered copper samples (x2), process conditions of sintering: $V=3000$ mm/min, $t=200$ °C, $S=0.3$ mm, $P=15$ W.

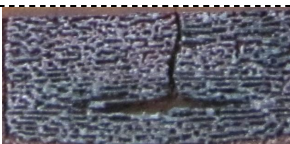
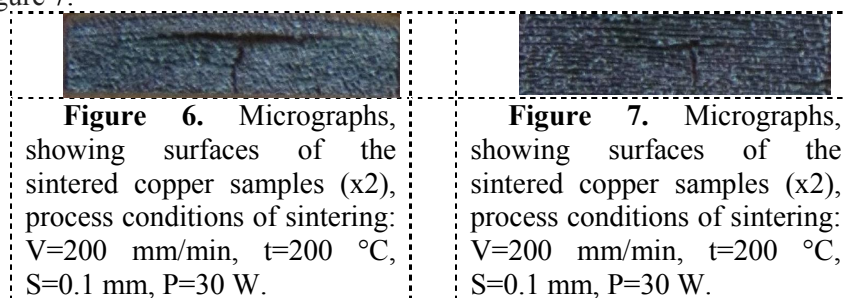


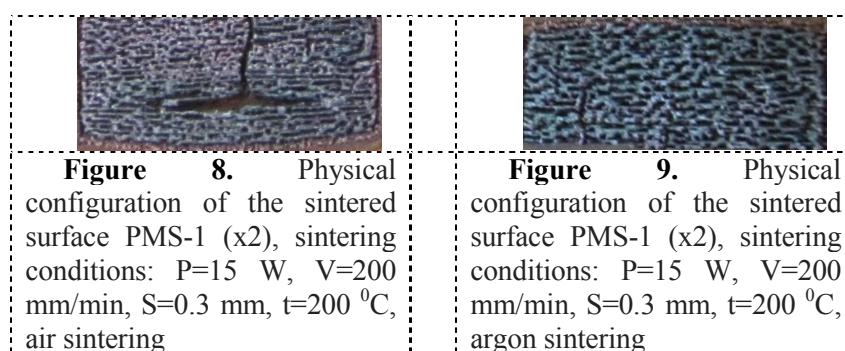
Figure 5. Micrographs, showing surfaces of the sintered copper samples (x2), process conditions of sintering: $V=200$ mm/min, $t=200$ °C, $S=0.3$ mm, $P=15$ W.

Increasing scanning step causes the augmentation of the sintered surface roughness R_z 600 to 700, figure 6 and figure 7.

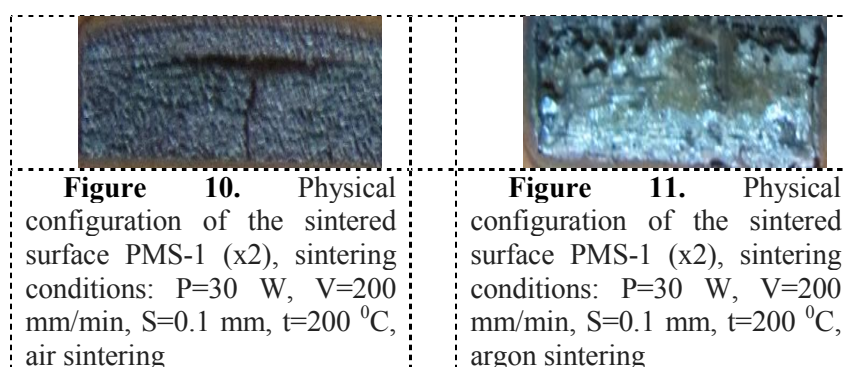


The temperature of pre-heating the powdered sample before sintering has only a slight effect on the roughness. Comparing the data of experiments and data calculated by formula 1, we have concluded that laser output power, velocity of laser beam displacement and scanning step are the main variables influencing on the sintered surface roughness, although the temperature of powder material pre-heating is to be taken into account.

The experiments are conducted to detect the dependence of the sintered surface layer on the shielding gas (argon), figures 8-11, and mechanical activation of the powder. Argon sintering results in improvement of the surface layer strength, without origination of cracks. Cross and length-wise cracks are not detected when sintering in argon, figure 9, sintering conditions: $P=15$ W, $V=200$ mm/min, $S=0.3$ mm, $t=200$ °C. The thickness of the sintered layer changes a little from 1.7 mm (air sintering) to 1.735 (argon sintering).

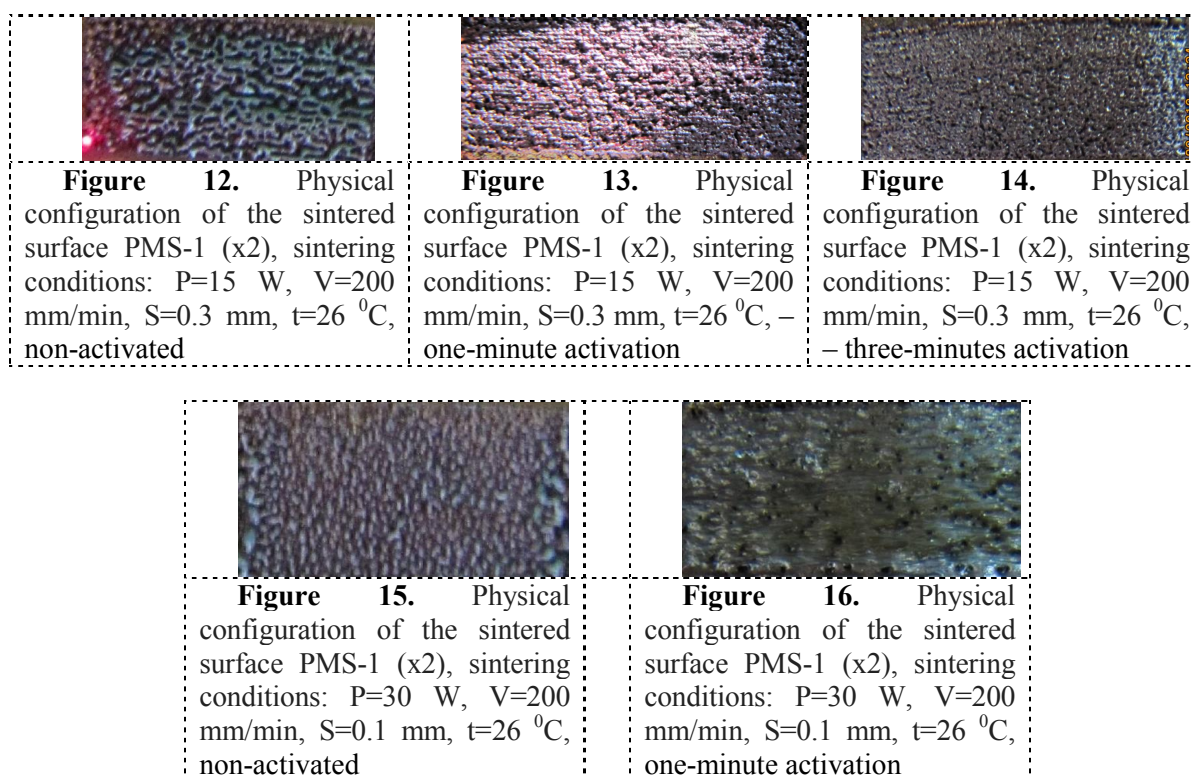


A sharp decline of the surface layer quality and strength becomes apparent when comparing the samples sintered in argon and in air in conditions: $P=30$ W, $V=200$ mm/min, $S=0.1$ mm, $t=200$ °C, shown in figures 10-11. The roughness changes from 750 to 115 μm , the thickness of the sintered layer does not change much, varying from 1.0 to 0.915 mm. There are no cross and length-wise cracks detected in the sample, sintered in argon.



Argon sintering has a significantly positive effect on the surface layer, which becomes less rough and there are no defects detected.

Powders are subject to one-minute and three-minutes machining in a centrifugal planetary-type mill AGO-2 in order to detect the influence of mechanical activation of powder on the sintered layer. In figures 12-14 there are images of powder composite PMS-1 layers sintered in various conditions for non-activated powder and powder of different degrees of activation. In figures 12-14 one can see that surface roughness of sintered pre-activated samples varies from 700 μm (non-activated powder) to 426 μm (powder, activated for three minutes) in sintering conditions $P=15\text{ W}$, $V=200\text{ mm/min}$, $S=0.3\text{ mm}$, $t=26^\circ\text{C}$.



Comparing the images of samples a conclusion can be drawn that mechanical activation has a significant influence on the sintered surface: coagulation and roughness decrease, the samples are more solid.

When analyzing the sintered layers of non-activated and activated powdered material, it is revealed that preliminary mechanical activation influences on the sintering process, improving the sintered surface, as the consequence, the diameter of coagulated particles gets smaller, roughness is decreased.

The comparison of graphs and observational results over the sintering process makes it obvious that increasing the power results in surface swelling, causing, therefore, shrinkage and melting. It is possible perhaps because of the rapidly growing thermal conductivity of the material at the moment of melting. Then the process is stabilized, and increasing power density has no effect on the thickness of the sintered layer.

Having processed a large amount of experimental data and detected an apparent change in the sintered surface of the powder material, figures 17-19 it is proposed to use the concepts of rough and finishing modes of laser sintering powder materials. This allows differentiating the modes of synthesizing the surface and the bulk of the prototype.

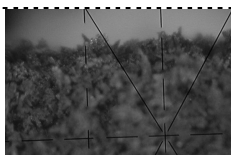


Figure 17. Images of the surface layer of sintered powder PMS-1 $\times(150)$, high-quality surface



Figure 18. Images of the surface layer of sintered powder PMS-1 $\times(150)$, swelling of the surface (increasing roughness),

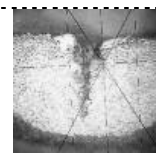
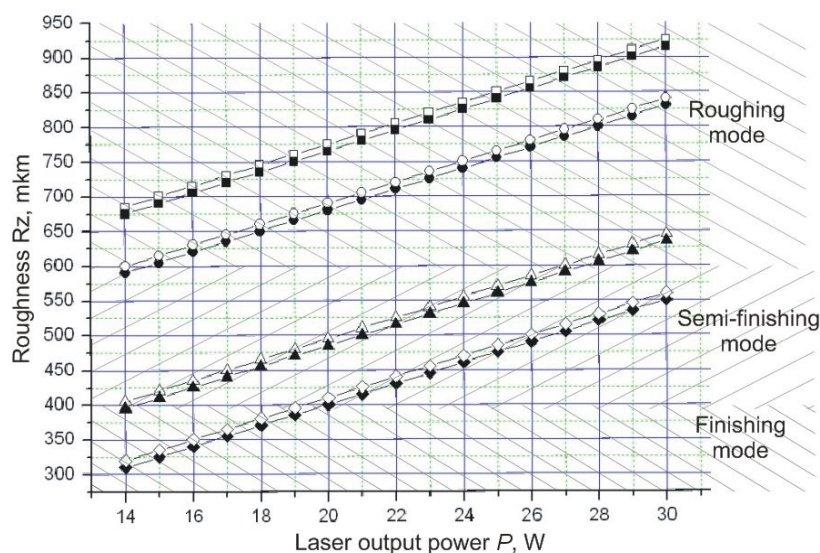


Figure 19. Images of the surface layer of sintered powder PMS-1 $\times(150)$, melting

As it is revealed in the conducted experiments the thickness of the sintered surface layer and its roughness R_z can be varied in definite limits via changing the modes of laser treatment. To synthesize a sintered surface of different quality the authors suggest differentiating conditions of forming the prototype surface and its bulk into rough, semi-finishing and finishing ones, figure 20.



- $V=200$ mm/min, $t=26$ °C, $S=0.3$ mm; $V=200$ mm/min, $t=200$ °C, $S=0.3$ mm;
- ◇— $V=200$ mm/min, $t=26$ °C, $S=0.1$ mm; $V=200$ mm/min, $t=200$ °C, $S=0.1$ mm;
- △— $V=300$ mm/min, $t=26$ °C, $S=0.3$ mm; $V=3000$ mm/min, $t=200$ °C, $S=0.3$ mm;
- ◇— $V=3000$ mm/min, $t=26$ °C, $S=0.1$ mm; $V=3000$ mm/min, $t=200$ °C, $S=0.1$ mm;

Figure 20 – Sintering modes for copper powder material

The rough sintering conditions are aimed at forming the bulk of the product. Increasing roughness of the surface (swelling) has a positive effect on the firm joint between the layers in this case.

The efficiency of layer-by-layer sintering is reduced considerably in semi-finishing conditions; however, no further processing of the prototype is required to make the surface of the specified quality and accuracy.

Finishing processing is performed in case of need. The finishing mode can be called accelerated one and it is based on the high density of laser output power in a short period of time. As the results, sublimation of micro-roughness peaks of the surface or plating the prototype surface are possible.

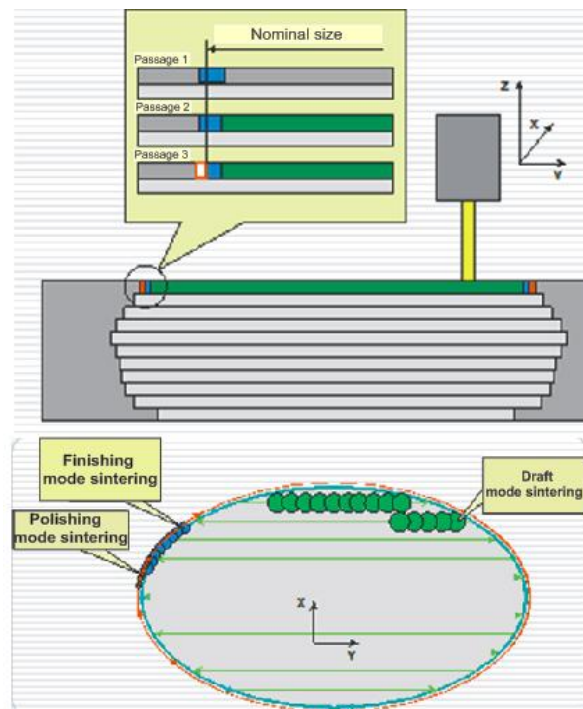


Figure 21. The strategy of single layer sintering

Conclusion

The paper describes the influence of laser sintering conditions and empirical dependence of the sintered surface layer on the sintering conditions, which allows controlling the manufacturing process of a high quality product. Controlled modifying the properties of the sintered surface layer is discussed via differentiating the process conditions into a semi-finishing mode for the surface and a rough mode for the bulk, that makes it possible to increase the efficiency of the sintering process without deteriorating quality of the product surface.

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